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Multi-Objective Voltage Optimisation Trade-off Assessment for Coupled HV and LV Networks

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Abstract— Real-time HV and LV network voltage optimisation and control are receiving significant attention from both academia and industry as a means of reducing consumer power consumption and increasing the capacity for utilization of low carbon technologies. In this study, a multi-objective optimisation problem involving the twin objectives of HV network loss reduction and LV network energy consumption reduction is considered. The potential trade-off that may exist between these two objectives is investigated using a detailed openDSS simulation of a coupled HV/LV network in the greater Manchester area in the UK. Optimisation of the voltage control devices is performed using a warm start oriented discrete coordinate descent method with a decomposition weighting technique employed to assess the trade-off between the objectives. The results show that, while a trade-off does exist, the much larger scale of LV energy reduction compared to the increase in HV losses means that the latter dominates the optimisation. When the objective functions are given equal weighting an 8.3% and 10.1% reduction is achieved in LV energy consumption and HV energy loss, respectively, compared to nominal operation.

Keywords— Conservation Voltage Reduction, multi-objective optimisation, co-ordinated voltage control, real time

I. INTRODUCTION

The UK Department of Energy and Climate Change's 2050 pathways analysis report^{*} predicts that electricity demand in the UK will double by 2050 due to the electrification of heating and transport. The high cost associated with installing new infrastructure to meet this demand, particularly in the context of supporting the increasing deployment of low carbon technologies (LCT) such as heat pumps, electric vehicles, and rooftop solar PV systems, presents distribution network operators (DNO) with many challenges. To offset the need for this investment DNOs are looking at strategies to maximise the utilisation of their existing assets. Among these, real-time HV and LV network voltage optimisation and control is receiving significant attention from both academia and industry as a means of reducing consumer power consumption and increasing the capacity for LCT.

Queen's University Belfast, in conjunction with Electricity North West Limited and the University of Manchester, are collaborating on 'Smart Street'[†], a network

voltage optimisation project funded by Ofgem's Low Carbon Networks Fund. The project involves a series of trials on 6 primary substations and 38 related distribution substations, representing around 62,000 customers in the greater Manchester area. As part of the project the University of Manchester have developed detailed openDSS simulations for these networks enabling comprehensive studies of active voltage management strategies to be undertaken.

The Smart Street project is exploring the use of voltage management techniques simultaneously across its HV and LV networks to achieve the twin objectives of reduced power losses on the HV networks and reduced energy consumption on the LV networks by manipulating OLTC transformer tap positions, meshing points, and capacitor banks on a half hour basis. The LV energy consumption reduction is achieved through CVR, a process of lowering the voltage of the power supplied to consumers [1], [2] and [3], while the HV energy loss reduction is normally achieved through transmission of power at higher voltages and through power factor correction with capacitor banks.

It is apparent that a reduction in energy consumption on the LV side will also result in a reduction of losses on the HV side due to reduced power flows. However, the need to maintain high voltages on the HV network may limit the capacity of LV transformers to deliver CVR on the LV network, hence the potential exists for a trade-off between loss reduction on the HV side and CVR on the LV side of the distribution network.

To provide a systematic evaluation of the potential trade-off that may exist between the two objectives of interest, we formulate the problem within a multi-objective optimisation framework. The study is conducted using detailed OpenDSS simulations of a coupled HV/LV network from the Smart Street trial networks, where the CREST[‡] tool has been employed to generate individual consumer load ZIP parameters representative of a sample winter day in the same region. Optimisation is performed using a warm start oriented discrete coordinate descent (ODCD) method [4]. A decomposition weighting technique is employed to explore the trade-off between the LV and HV objectives in the inequality constrained multi-objective optimisation problem [5]. Particle swarm optimisation is also employed to verify

^{*} <https://www.gov.uk/government/uploads/.../216-2050-pathways-analysis-report.pdf>

[†] <http://www.enwl.co.uk/smartstreet>

[‡] <http://www.lboro.ac.uk/research/crest/demand-model/>

the effectiveness of the ODCD optimisation method, which has been adopted with real-time implementation in mind.

The remainder of this paper is organised as follows. Section II presents the methodology adopted to assess the benefit achieved by the optimisation process, then section III describes the proposed optimisation framework and related concepts. Section IV describes the case study selected for this study. The optimisation results are presented and detailed in section V. Finally, section VI presents the conclusions.

II. ASSESSMENT METHODOLOGY

Quantifying the energy reduction performance of active voltage management techniques in the field is challenging due to the lack of repeatability of load conditions, which are inherently stochastic and weather dependent. These challenges can be avoided by employing simulated network models. This allows energy consumption and losses to be simulated for both nominal and optimised control device settings with otherwise identical conditions, allowing the energy reduction performance of a particular strategy to be explicitly quantified.

A. Energy reduction measurement

For a given HV or LV network, performance of a particular optimisation strategy in terms of energy loss or consumption reduction is expressed as a percentage of the energy loss or consumption of the network under nominal conditions, that is:

$$\Delta E(\%) = \frac{1}{48} \sum_{i=1}^{48} \left(\frac{E_o(i) - E_{opt}(i)}{E_o(i)} \right) \times 100 \quad (1)$$

Here, $E_o(i)$ and $E_{opt}(i)$ are the energy loss or consumption of the network for nominal and optimized dynamic operation, respectively. This is computed for every 30-minute time interval over a 24-hour period, reflecting the optimisation update frequency and the need to account for the daily load cycle.

B. Time-varying load demand

Employing accurate time-varying load models that capture the voltage dependency of load demand is essential for the validity of simulation based assessment. In the Smart Street network simulations ZIP load models resolved to one minute intervals are used to represent individual LV network consumers over a 24 hour period [1]. For real power, the ZIP model for the k -th consumer during the i -th time interval is given by

$$P_k(i) = P_{ok}(i) \left[\hat{Z}_k(i) \cdot \left(\frac{V(i)}{V_o} \right)^2 + \hat{I}_k(i) \cdot \left(\frac{V(i)}{V_o} \right) + \hat{P}_k(i) \right] \quad (2)$$

where, P and P_o denote the consumed active power for the current voltage $V(i)$ and the nominal voltage V_o ,

respectively, and parameters \hat{Z} , \hat{I} and \hat{P} represent constant impedance, constant current and constant power load dependencies, for each consumer at each sample instant. These values were generated using the CREST tool[§], a high-resolution stochastic model of domestic thermal and electricity demand in the UK developed by University of Loughborough, at one minute intervals over a 24 hour period for a representative winter day scenario for each consumer on the Smart Street trial LV networks.

Aggregated ZIP parameters for each LV network, are then computed using the following equations:

$$\begin{aligned} Z_{agg}(i) &= \frac{\sum_k \hat{Z}_k(i) \cdot P_{ok}(i)}{\sum_k P_{ok}(i)}; \quad I_{agg}(i) = \frac{\sum_k \hat{I}_k(i) \cdot P_{ok}(i)}{\sum_k P_{ok}(i)}; \\ P_{agg}(i) &= \frac{\sum_k \hat{P}_k(i) \cdot P_{ok}(i)}{\sum_k P_{ok}(i)} \end{aligned} \quad (3)$$

where, Z_{agg} , I_{agg} and P_{agg} are the aggregated ZIP model parameters for active power of a given LV network. Similar expressions apply for reactive power load models [6].

III. OPTIMISATION METHODOLOGY

In the Smart Street trials, optimisation of the voltage control devices is performed centrally, with updates performed every 30 minutes. Mindful of the need to achieve real-time operation, in this study the low-complexity warm start oriented discrete coordinate descent (ODCD) method [4] has been selected to perform the optimisations. In this section, we first define the multi-objective optimisation problem to be solved, and then briefly introduce ODCD.

A. Multi-objective optimisation formulation

A multi-objective optimization problem can be defined as:

$$\min_{\mathbf{x}} \mathbf{F}(\mathbf{x}) = (f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_k(\mathbf{x})) \quad s.t. \quad \mathbf{x} \in S, \quad (4)$$

where k is the number of scalar objective functions and \mathbf{x} is the vector of decision variables, with a domain of definition $S \subseteq R^n$. For each $\mathbf{x} \in S$ there is a corresponding $\mathbf{F}(\mathbf{x}) \in C$, where C is referred to as the objective space [5].

1) CVR as a multi-objective optimisation problem

Within the aforementioned framework CVR is naturally cast as a multi-objective optimisation problem with $k = 2$ in equation (4), $f_1(\mathbf{x}) = HVL(\mathbf{x})$ and $f_2(\mathbf{x}) = LVE(\mathbf{x})$. Here, $HVL(\mathbf{x})$ and $LVE(\mathbf{x})$ are the HV network power loss and LV network energy consumption objective functions, respectively, and \mathbf{x} is the vector of voltage control device

[§] <http://www.lboro.ac.uk/research/crest/demand-model/>

settings that can be manipulated by CVR. To enable evaluation of the trade-off between both objectives, we introduce the weighted decomposition method with weights $w_1 = \alpha, w_2 = (1 - \alpha)$ [9], that is

$$f_D(\mathbf{x}) = \alpha HVL(\mathbf{x}) + (1 - \alpha) LVE(\mathbf{x}), \quad 0 \leq \alpha \leq 1 \quad (5)$$

Solving for different values of α allows the Pareto front to be determined, and hence the trade-off between $HVL(\mathbf{x})$ and $LVE(\mathbf{x})$ to be quantified. The advantage of this formulation is that the cost function being optimised is simply a generalisation of the standard CVR cost function, i.e. the case when $\alpha = 0.5$, and hence generating the closed loop dynamic CVR solutions for different values of α involves a straightforward application of the existing CVR optimisation methodology. Moreover, only a relatively small number of optimisations need to be performed, since the search space is over the range of α . Note that $\alpha = 0$ corresponds to optimising for LVE only, ignoring the high voltage network power losses, and $\alpha = 1$ corresponds to optimising HVL, ignoring the impact on LV network energy consumption. These two extremes define the two end points of the Pareto front of interest in our trade-off assessment.

2) Problem formulation

The multi-objective optimisation problem in this study is a minimization problem with inequality constraints. The CVR objective function for a given time period is defined as equation (5), which is the summation of the high voltage network power losses and low voltage network energy consumption. The HV network power losses are a summation of the power losses at the HV transformers, HV capacitor and high voltage lines that is:

$$HVL = \Delta P^L + \Delta P^{Tr} + \Delta P^C \quad (6)$$

where the ΔP s are the power losses in the HV lines (L), transformers (Tr), and capacitors (C). The LV network energy consumption is defined as:

$$LVE = \sum_{k=1}^{NL} (P_k) \quad (7)$$

where the P_i is active power consumption of k -th consumer, NL is the total number of consumers. The optimisation is subject to the constraint that the voltage along each feeder at each secondary bus should be within specified limits, that is:

$$V_{i,\min} < V_i < V_{i,\max} \quad \text{at the } i^{th} \text{ monitoring point} \quad (8)$$

In general terms the mathematical formulation of the optimisation problem can be expressed as

$$\min_{\mathbf{x}} \{f_D(\mathbf{x})\} \quad \text{subject to} \quad \begin{cases} g_i(\mathbf{x}) < 0 \\ h_i(\mathbf{x}) < 0 \end{cases}, \quad i = 1 \text{ to } NV \quad (9)$$

where $g_i(\mathbf{x}) = V_i(\mathbf{x}) - V_{i,\max}$ and $h_i(\mathbf{x}) = V_{i,\min} - V_i(\mathbf{x})$.

Here $g_i(\mathbf{x})$ and $h_i(\mathbf{x})$ define the constraints on the higher and lower level of permissible voltage, respectively. The symbol \mathbf{x} denotes the vector of optimization (control) variables, one for each controllable device in the distribution network. For capacitors $x_j \in \mathbf{x}$ is an integer value from 0 to C_{\max} in steps of 50 kvar, while for transformers it is an integer corresponding to the tap position from 1 to Tap_{\max} . Evaluating (5), $g_i(\mathbf{x})$ and $h_i(\mathbf{x})$ for a given \mathbf{x} involves simulating the detailed OpenDSS network models for the control device setting represented by \mathbf{x} to determine the network power flows, the associated power losses and corresponding voltage levels at each node in the network.

To solve the linear inequality constrained discrete nonlinear multi-objective minimization problem we convert it to an unconstrained problem by including the constraints in the objective function as additional penalty terms. The penalty term, $PF(\mathbf{x})$, takes the form

$$PF(\mathbf{x}) = \sum_{i=1}^{NV} \left(\xi_i^H |g_i(\mathbf{x})|_+ + \xi_i^L |h_i(\mathbf{x})|_+ \right) \quad (10)$$

where ξ_i^H and ξ_i^L are the penalty coefficients for high and low voltage violations, respectively, for the i^{th} monitoring point. The modified cost function is then given by:

$$\bar{f}_D(\mathbf{x}) = PF(\mathbf{x}) + f_D(\mathbf{x}) \quad (11)$$

If a system is not experiencing any voltage violations, $PF(\mathbf{x})$ will be equal to zero.

B. Warm-start ODCD

ODCD is essentially a gradient descent algorithm applied in the discrete domain. The gradient is computed by evaluating the change in the objective function with respect to a step change in each control variable individually [12], where the step size is the smallest discrete increment possible with each control variable. The update direction is then selected as the coordinate direction that yielded the largest negative gradient.

Due to the potential for the basic ODCD algorithm to get trapped in local minima if initial conditions are not within the basin of attraction of the optimal solution, a **warm start** implementation is employed, where the optimum control settings from the previous time period are selected as the initial conditions for the current optimisation step [4]. For the first iteration, where a priori estimates are not available, the optimisation is repeated several times with different randomly selected initial conditions and the best solution retained.

IV. CASE STUDY

In order to evaluate the potential HV/LV trade-offs and the performance of the adopted optimization method

(ODCD), a HV/LV network from the Smart Street trial area was selected as a case study for CVR optimisation.

A. Network configuration

The basic information for the selected network is shown in Table I. There are two 33kV/6.6kV 10000kVA transformers connected in parallel at the primary substation. This substation feeds 52 LV networks, only one of which is equipped with an OLTC transformer at the LV level. In total 10303 customers are supplied by this HV/LV network. An OLTC is installed on the primary side of the HV substation, which adjusts the voltage from -17.16% to +5.72% of the nominal setting in 17 steps of 1.43%. A 200 kvar circuit capacitor is installed at the HV level and can be switched in increments of 50 kvar.

TABLE I. BASIC INFORMATION FOR THE SAMPLE NETWORK.

Network:	Sample Network
Voltage Level:	33kV/6.6kV
Primary Transformer:	2 * 10000kVA
Number of LV Networks:	52 (includes 7 trial and 45 non-trial networks)
Number of Customers:	10303
Load Composition:	94% residential + 6% commercial and industrial
HV OLTC:	From -17.16% to +5.72%, 17 steps of 1.43%
LV OLTC:	From -8% to +8%, 9 steps of 2%
LV NLTC	From -5% to +5%, 5 steps of 2.5%
Capacitors	1 * 200kVAr

B. Optimisation definitions

The sample network was simulated in openDSS for a typical winter day load scenario. Matlab was used as a wrapper programme to perform CVR optimisation and update the settings of the controllable devices. While load profiles and power system states were determined at a resolution of 1 minute, for consistency with actual operation in the trials, optimisation and updating of control devices was performed on a half hourly basis.

The voltage control devices considered were the HV network capacitor bank, HV transformer tap positions, and OLTC and NLTC LV transformer tap positions. The NLTC transformers, which have 5 tap positions, were fixed in a single position for the full day, whereas the other control devices were updated on a half hourly basis.

The CVR objective function was defined as in eq. (9) with the voltage constraints as specified in the BS EN50610 standard. The standard requires that 95% of the 10 minutes moving average voltage values at the LV level should be within +10% and -6% of the nominal voltage (230V) and should never be below -15%. The voltage limits at the HV side are $\pm 6\%$ of the nominal voltage (6.6kV).

In all simulations, the CVR optimized networks are compared against a *base case* of nominal operation where all the network devices are at nominal settings. The nominal setting for this study was where all the taps for all transformers including HV and LV OLTCs, and NLTCs

were fixed in their middle location over the whole sample day and the HV capacitor bank was switched off.

V. RESULTS

To solve the multi-objective optimisation problem with the proposed method (decomposition technique), and assess the trade-off between the twin objective functions for the case study network, an iterative study has been considered where the cost function is optimised in each time interval for a range of α values from zero to one in increments of 0.01.

Fig. 1 shows the trade-off between the two objective functions (HVL, LVE) for three different time intervals during the sample winter day ((a) off-peak (4 am), (b) midday (12 pm), and (c) peak (6 pm)). In each plot the red dots are the complete set of feasible solutions generated by an exhaustive evaluation of device control setting combinations. The blue line with pentagram markers shows the Pareto front derived by applying the decomposition technique to this set of feasible solutions for varying α . The markers define the set of Pareto solutions. The other set of results, shown as a black line (with pink square markers), is the Pareto front (set) estimated directly by employing ODCD with different values of α . It can be seen the ODCD estimates are not an exact match for the Pareto set, but in all cases converge to solutions close to the optimal set.

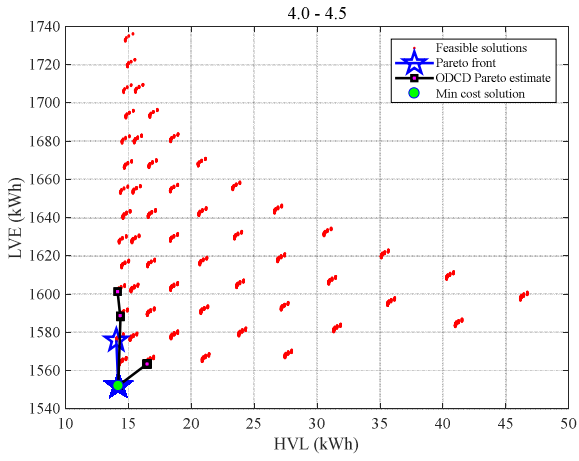
Values on or close to the Pareto front can be considered as candidate solutions to the optimisation problem. The choice between solutions depends on end-user priorities with regard to the different objectives. If the overall consideration is the total energy cost then this corresponds to applying an equal weighting to both objective functions ($\alpha = 0.5$). Fig. 2 shows how the optimum solution relates to the Pareto front in this instance, with the optimum point highlighted as a green circle.

Comparing results it can be seen that the LVE – HVL trade-off varies with the time of day /load on the network. However, the much larger scale and variation in LVE compared to HVL means that the minimum cost solution is dominated by minimisation of the LVE component.

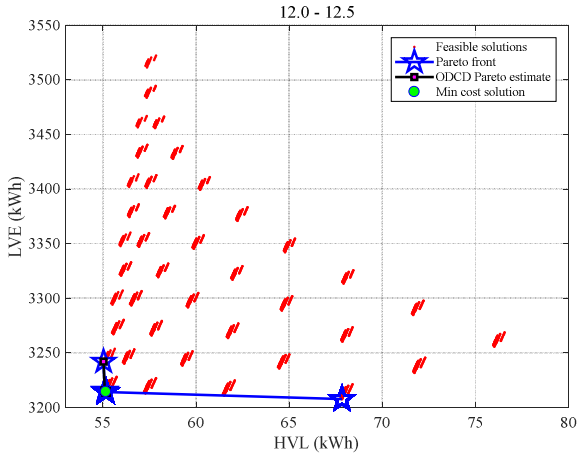
A. The selected solution

The optimum solution for each time-interval is selected as the ODCD one which yields the minimum \bar{f}_D when $\alpha = 0.5$. Fig. 3(a) shows the 10 minutes moving average of the minimum voltage over the sample day before and after optimisation. As can be seen the voltage profile after optimisation (the blue line) is relatively flat and close to the lower limit throughout the day.

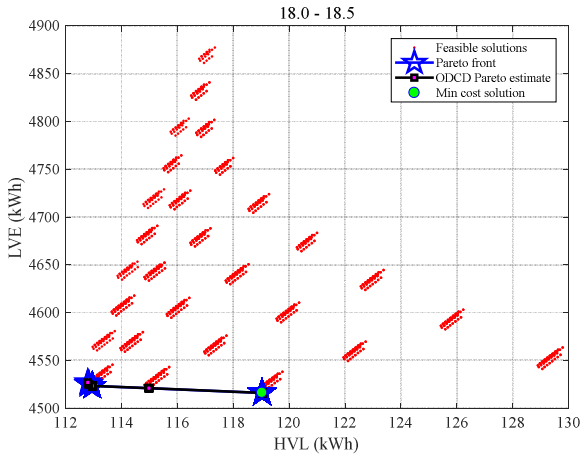
Fig. 3(b) displays the tap positions of the two HV OLTC transformers over the sample winter day. The selection of higher taps during peak times recovers the voltage drop at the end of line. The lowest tap positions have been selected for all the LV transformers including OLTC and NLTCs for the whole day, and zero for the HV capacitor as well. In the interest of clarity, these results have not been plotted.



(a) LVE-HVL Trade-off from 04.00-04.30



(b) LVE-HVL Trade-off from 12.00-12.30



(c) LVE-HVL Trade-off from 18.00-18.30

Fig. 1 Trade-off between LVE and HVL; (a) off-peak (4 am); (b) midday (12 pm) and (c) evening peak (6 pm).

Fig. 4 shows the half-hourly HVL and LVE values for the nominal and optimised setting over the sample winter day. As can be seen, HVL and LVE are reduced for each half hour throughout the day. Table II quantifies the average percentage reduction in HVL and LVE after optimisation in comparison with the nominal operation.

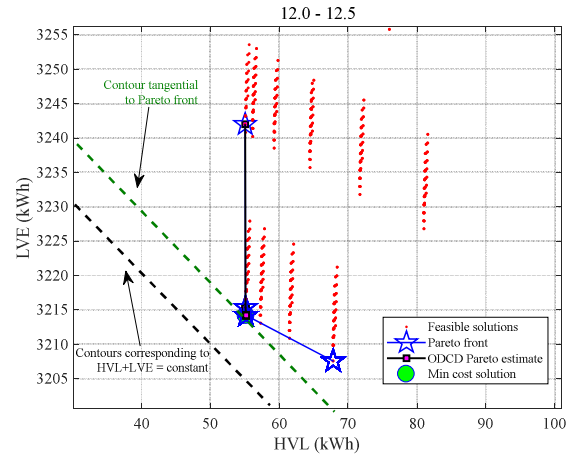
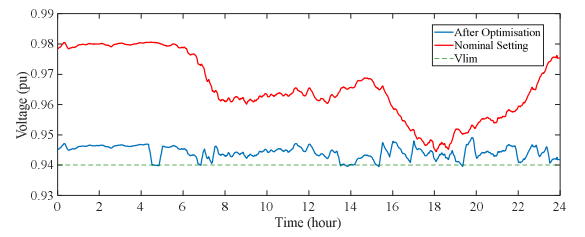
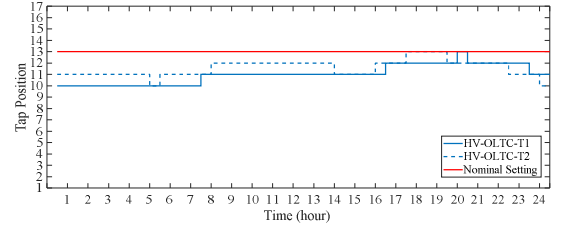


Fig. 2. Zoomed-in plot of the midday trade-off plot (Fig. 3(b)) with the same scale used for both the LVE and HVL axes.

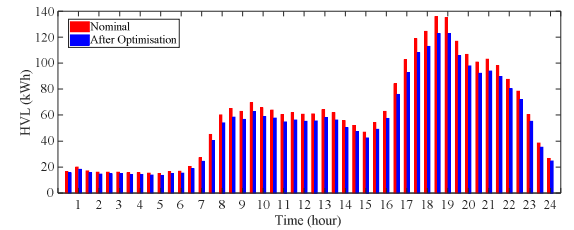


(a) minimum voltage profiles

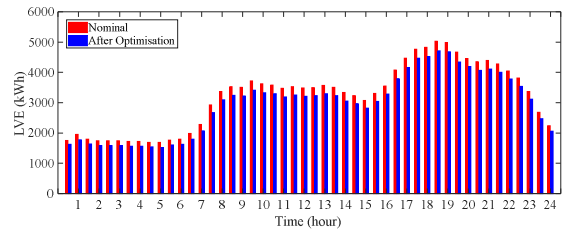


(b) transformer tap positions

Fig. 3. (a) 10 minutes moving average of the minimum voltage on the network over the sample day before and after optimisation, and (b) HV tap positions for the OLTC transformers during the optimisation period.



(a) HV Power losses



(b) LV energy consumption

Fig. 4. (a) HV power losses, and (b) LV power consumption before and after optimisation over the sample winter day.

TABLE II. THE AVERAGE PERCENTAGE REDUCTION IN HVL AND LVE OVER THE SAMPLE DAY WHEN THE OBJECTIVES ARE EQUALLY WEIGHTED.

Quantity	LVE	HVL
ODCD- ΔE (%)	8.3	10.1
PSO- ΔE (%)	8.4	10.3

B. ODCD versus PSO

To assess the quality of solutions generated by ODCD, a comparison was undertaken between the robust ‘warm start’ ODCD implementation and Particle Swarm Optimisation (PSO) [7],[8], a state-of-the-art global search algorithm. The results for both optimisation methods are presented in Table II. As can be seen ‘warm start’ ODCD and PSO yield very close results for both LVE and HVL reduction. Computationally, there is a huge difference in performance between the ‘warm start’ ODCD and PSO. ODCD is nearly 100 times faster than PSO for this problem. Since PSO represents the ‘global optimum’ solution at each iteration it can be concluded that the ‘warm start’ ODCD is a competitive alternative to PSO and an effective optimisation method for the CVR optimisation problem.

Note that while exhaustive search results were presented in the paper for selected time intervals to highlight the Pareto front and assess the quality of solutions obtained by ODCD, it is not a practical or scalable approach to finding the optimal settings. For the case study considered the computation time for the exhaustive search was 1000 times greater than when using ODCD to estimate the Pareto set.

VI. CONCLUSIONS

The potential trade-off in HV losses and LV energy consumption when undertaking dynamic multi-objective voltage optimisation of coupled LV and HV networks has been investigated using a detailed simulation of a distribution network in the UK. Simulation studies were undertaken using a combination of Matlab for optimisation and OpenDSS for the network simulation. Time-varying consumer load profiles resolved to individual consumer level were generated for a representative winter day scenario and embedded into the simulations to achieve robust and reliable CVR results. Warm start Oriented Discrete Coordinate Descent (ODCD) was employed as a scalable optimisation methodology and benchmarked against PSO and a full enumeration of all feasible solutions. The main conclusions of the study are as follows:

- A trade-off does exist between LVE and HVL, the exact nature of which depends on the time of day and hence load on the network. However, in practical terms LVE is much greater in magnitude than HVL with the result that it dominates the optimisation results.
- Warm start ODCD yields very close performance to the state-of-the-art Particle Swarm Optimisation global search technique and also very close results to an exhaustive search for off-peak and peak loads, while being much less computationally intensive.
- CVR voltage optimisation simulation studies using ODCD show the potential for LVE and HVL reduction of the order of 8.3% and 10.1%, respectively.

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